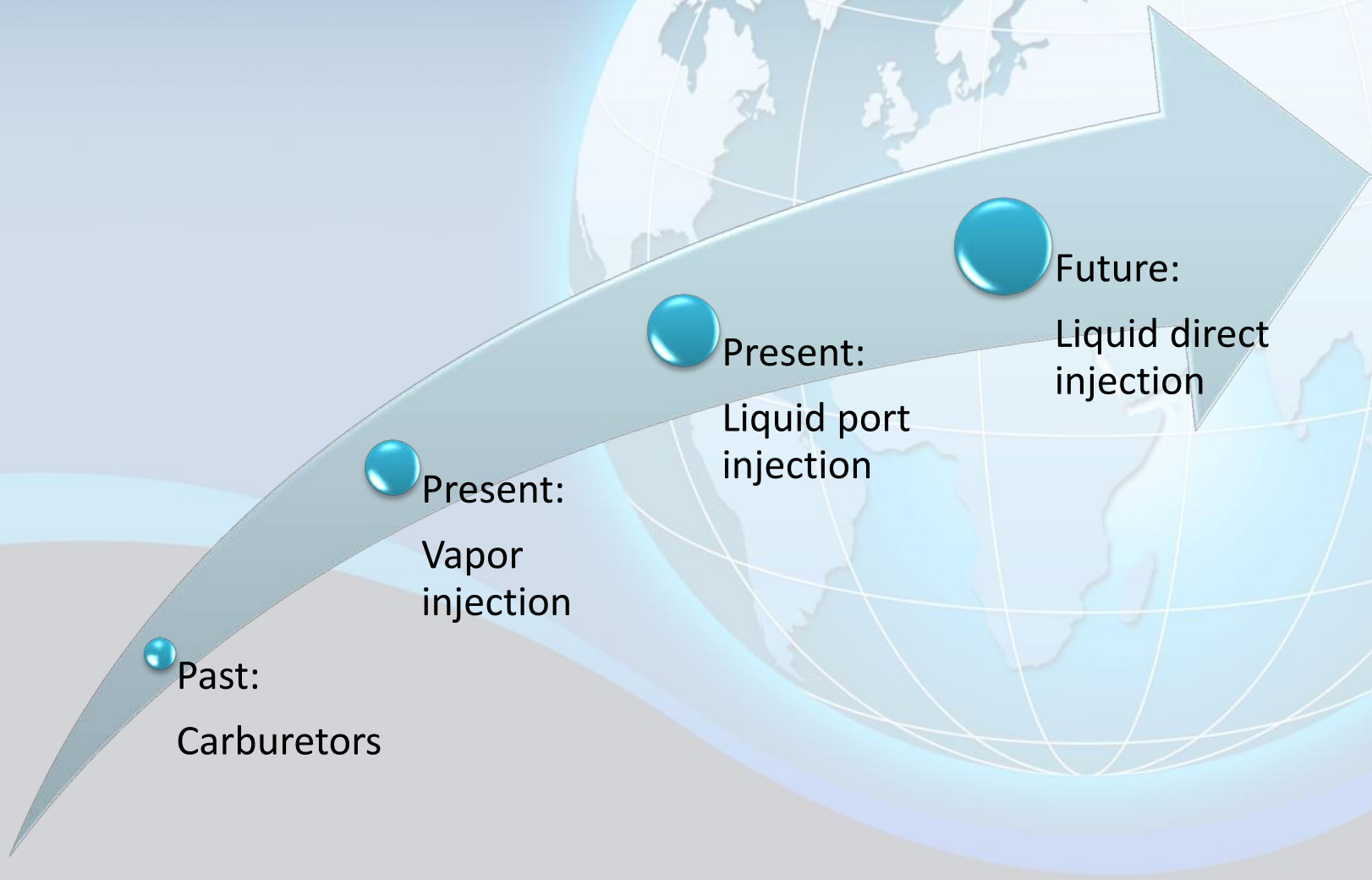


How Propane Autogas Can Enable High Efficiency Engines



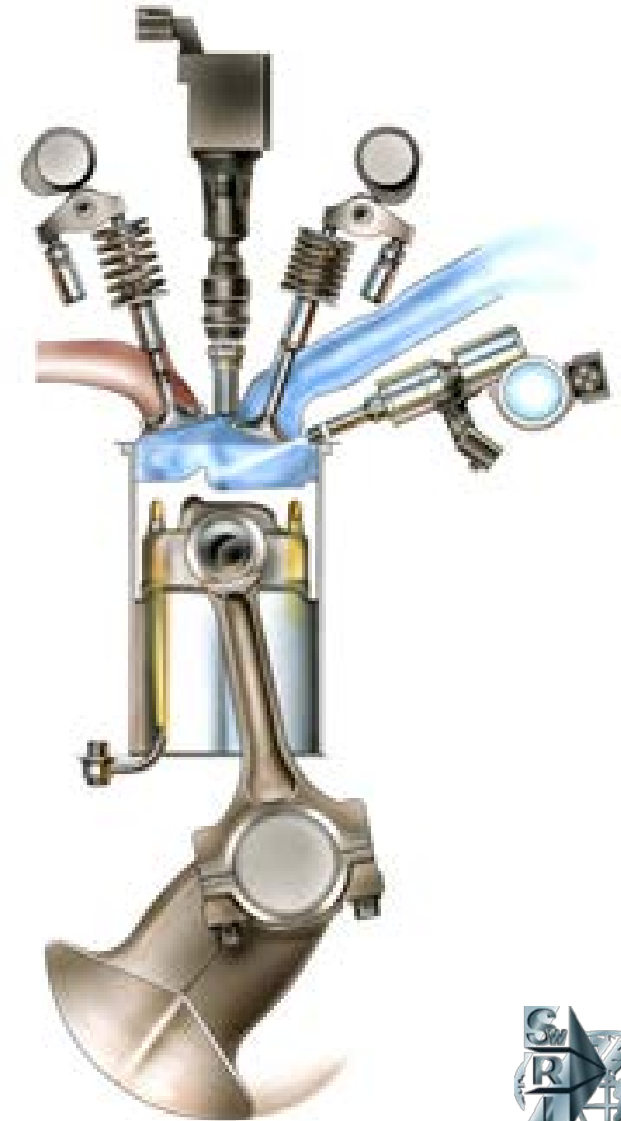
Nov. 13, 2014

State of the Art for Propane Autogas

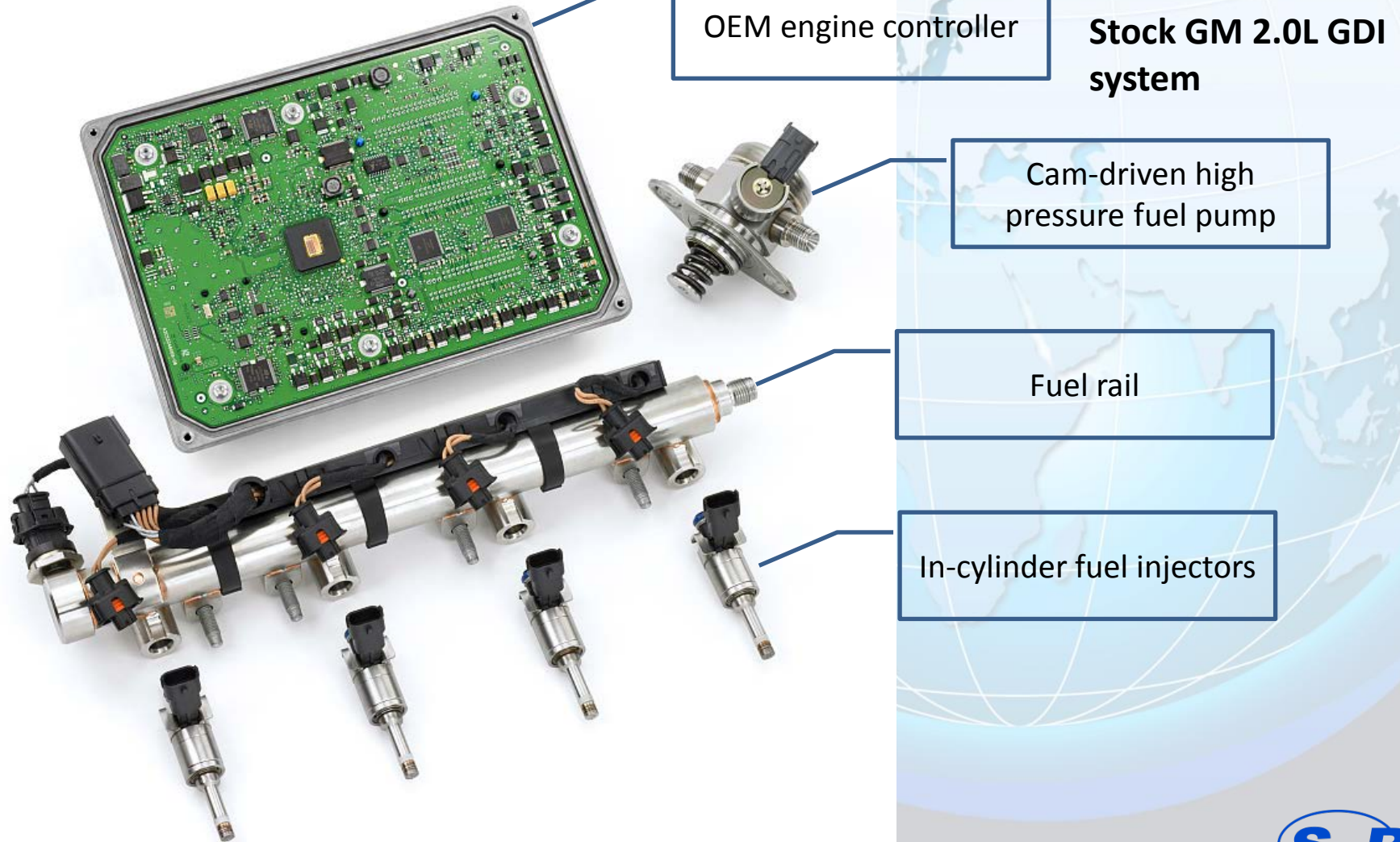


What is Direct Injection?

- Fuel injected directly into the cylinder
- High pressure fuel injectors operate at up to 3000 psig
- In cylinder cooling reduces knock
- Permits high compression ratios (up to 14:1)



Direct Injection System



Advantages of Autogas Direct Injection

- Opportunity: use stock GDI system to inject liquid LPG directly into the engine cylinder
- Higher performance
 - Does not displace intake air
 - Fuel vaporizes in-cylinder, cooling charge
 - Permits higher knock-limited boost pressure
 - Permits more optimized ignition timing
 - LPG has higher octane than gasoline, enabling further improvements in engine efficiency
- Lower emissions than DI gasoline
 - HC, CO, NO_x, CO₂, PM
- Multi-fuel capability
 - Could run on autogas, gasoline, or E85
- Lower cost conversions compared to PFI
 - Eliminates add-on LPG fuel rail and injectors

The background features a stylized globe with white grid lines on a blue gradient. A semi-transparent blue rectangle is centered over the globe. The title 'Light Duty' is written in white, bold, sans-serif font within this rectangle.

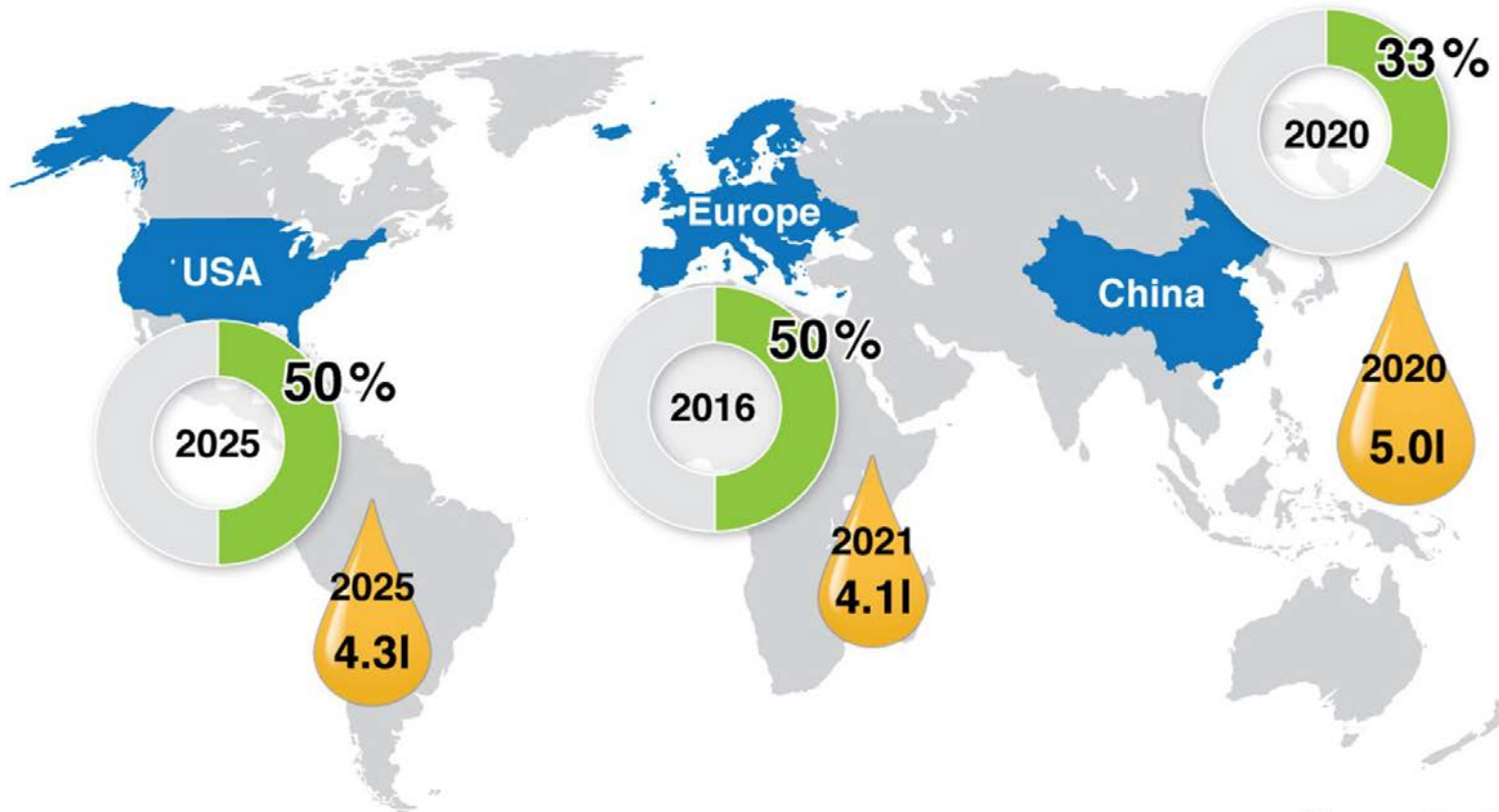
Light Duty

GDI Market Penetration

Projected sales of new cars with direct injection

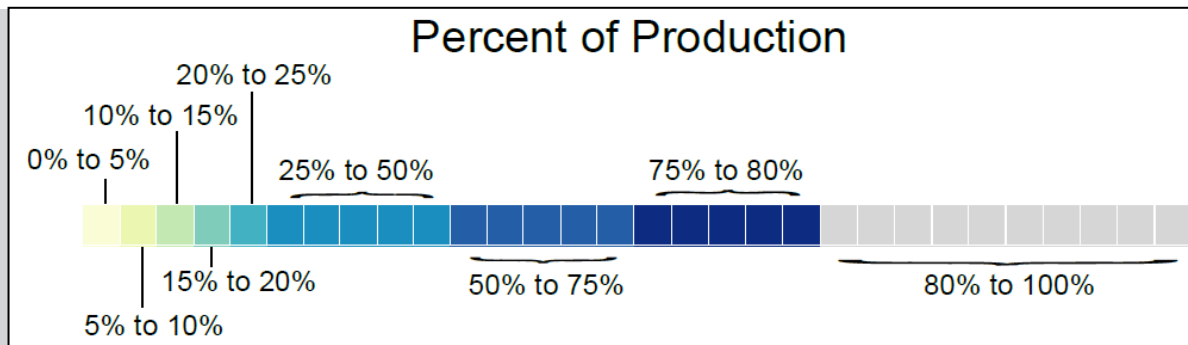
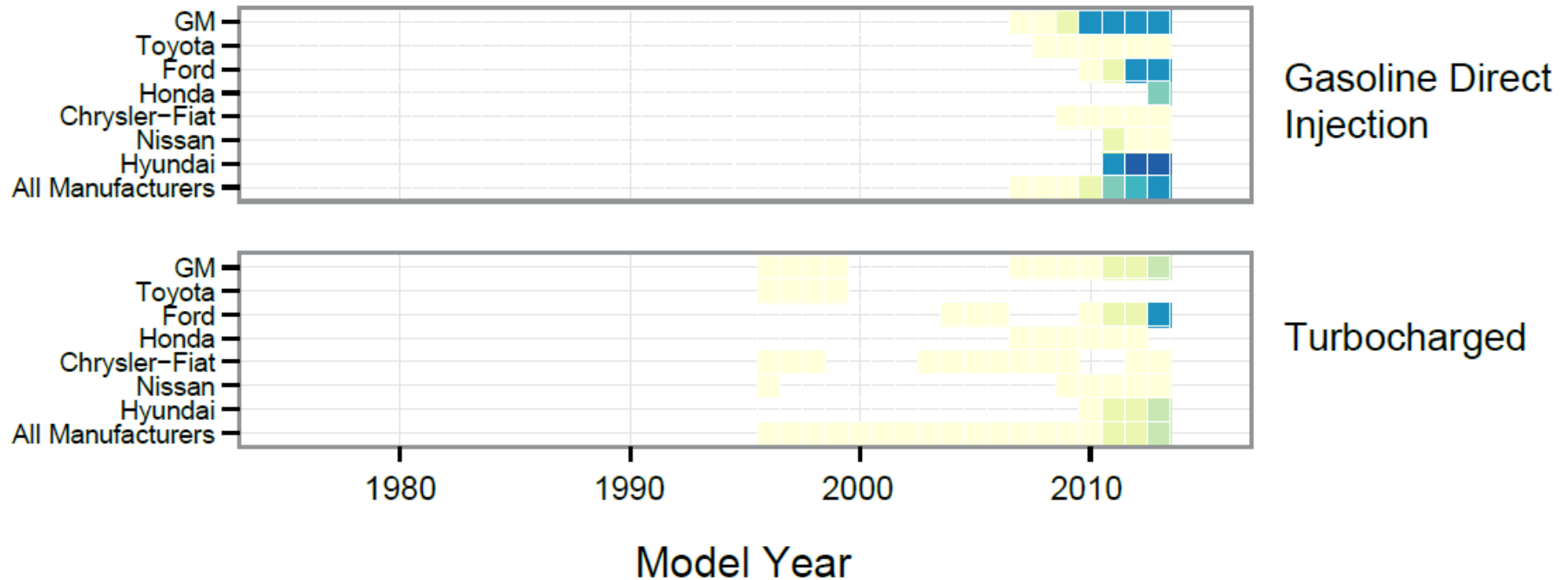
■ Annual share of new cars with gasoline direct injection

💧 Statutory emissions limit expressed as liters of gasoline per hundred km



Source: Bosch

U.S. GDI Market Penetration by Manufacturer



Source: EPA, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends:1975 Through 2013*

Engine Trends for High Efficiency

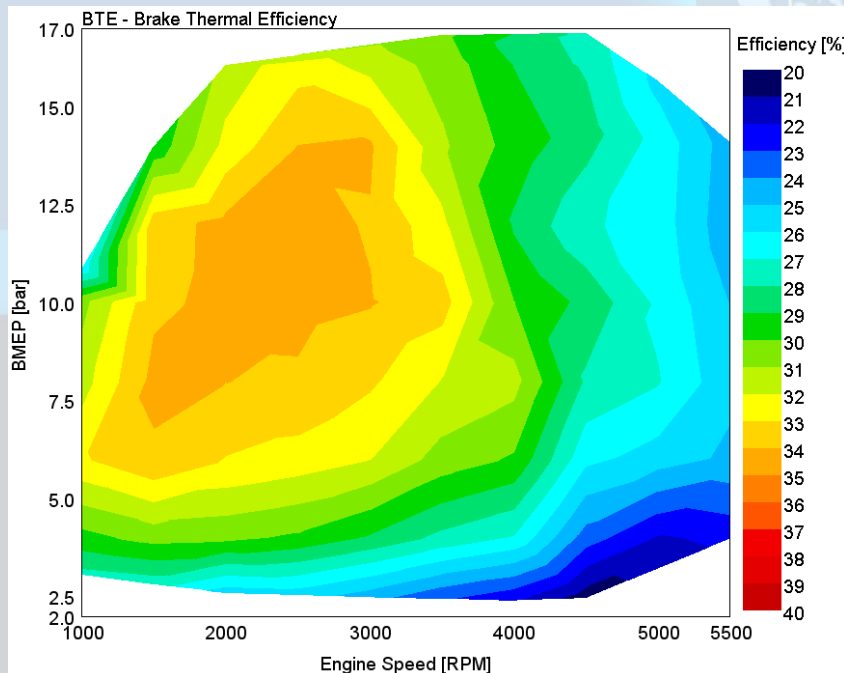
- **Downsized EcoBoost engines for Ford pickups**
- **2015 F150**
 - 3.5L V6 = 6.2L V8
 - 2.7L V6 = 5.3L V8
 - Direct injection
 - Twin-turbo



Downsizing Limited by Low Octane

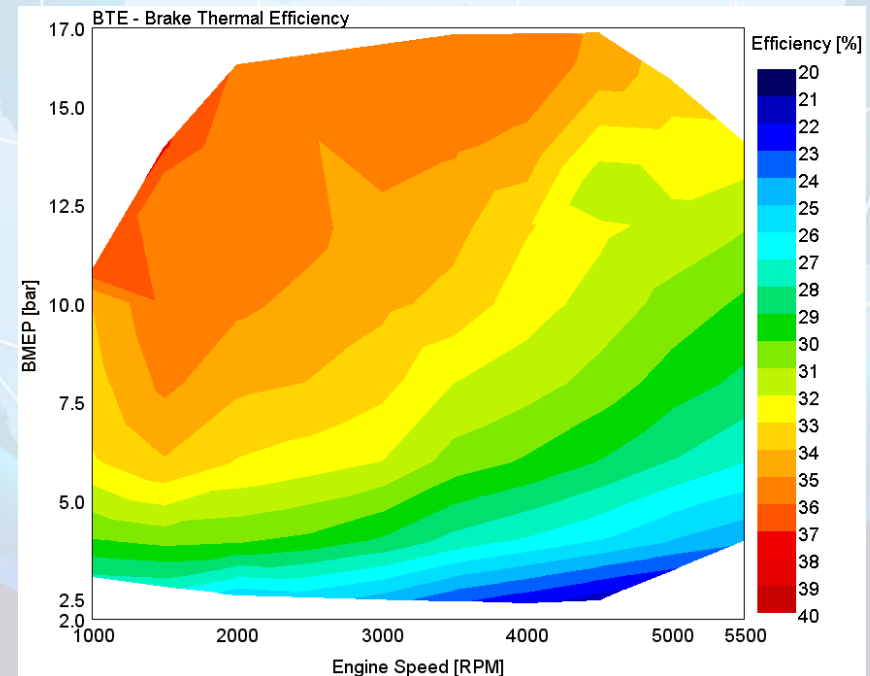
Stock Gasoline Calibration

- Poor BTE at high power due to retarded spark & enrichment



GT Power Projection

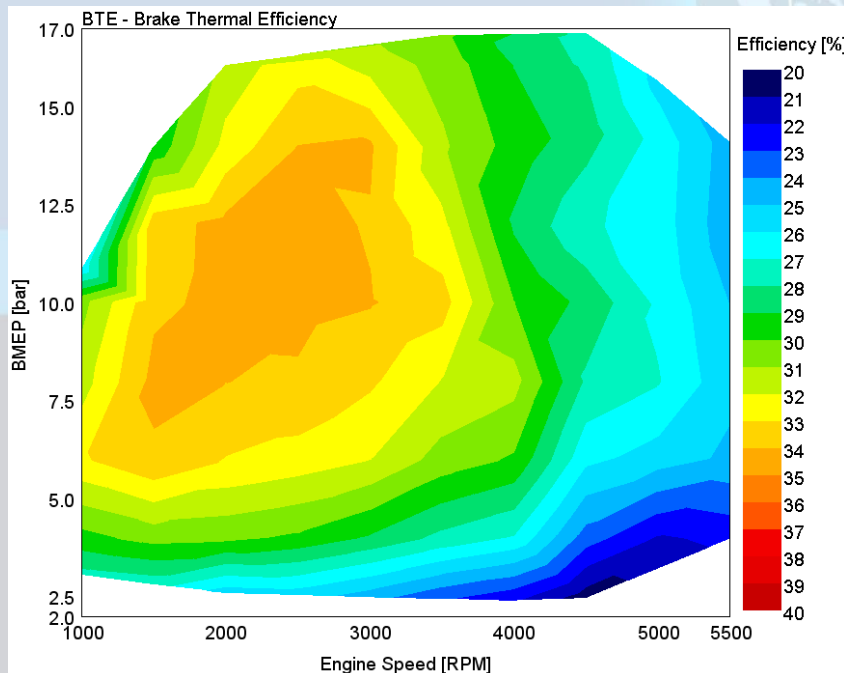
- MBT timing
- Stoich at all points



Effect of Compression Ratio

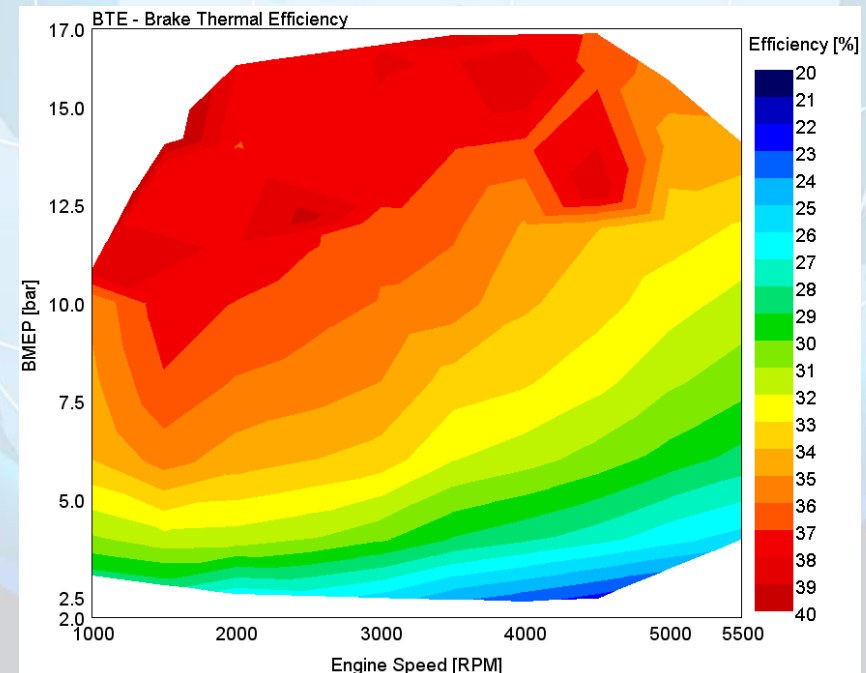
Stock Calibration

- 9:75:1 compression ratio



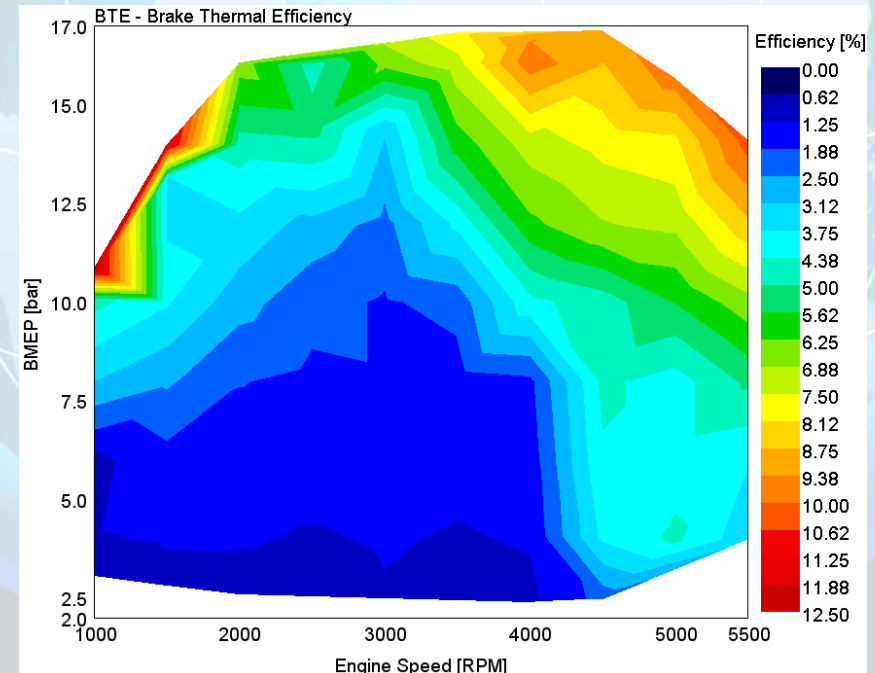
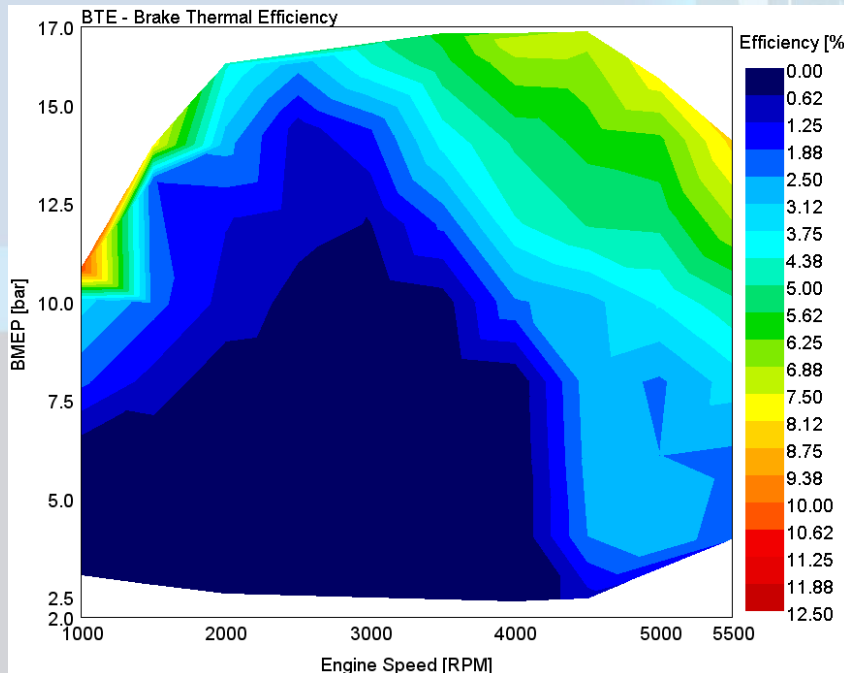
GT Power Projection

- MBT timing
- Stoich at all points
- 12:1 compression ratio



GT Power Projected BTE Deltas

- MBT timing
 - Stoich at all points
 - 9.75:1 compression ratio
- MBT timing
 - Stoich at all points
 - 12:1 compression ratio





Demonstration of Autogas Direct Injection in a Production Ford 3.5L EcoBoost Engine

3.5L EcoBoost Testing

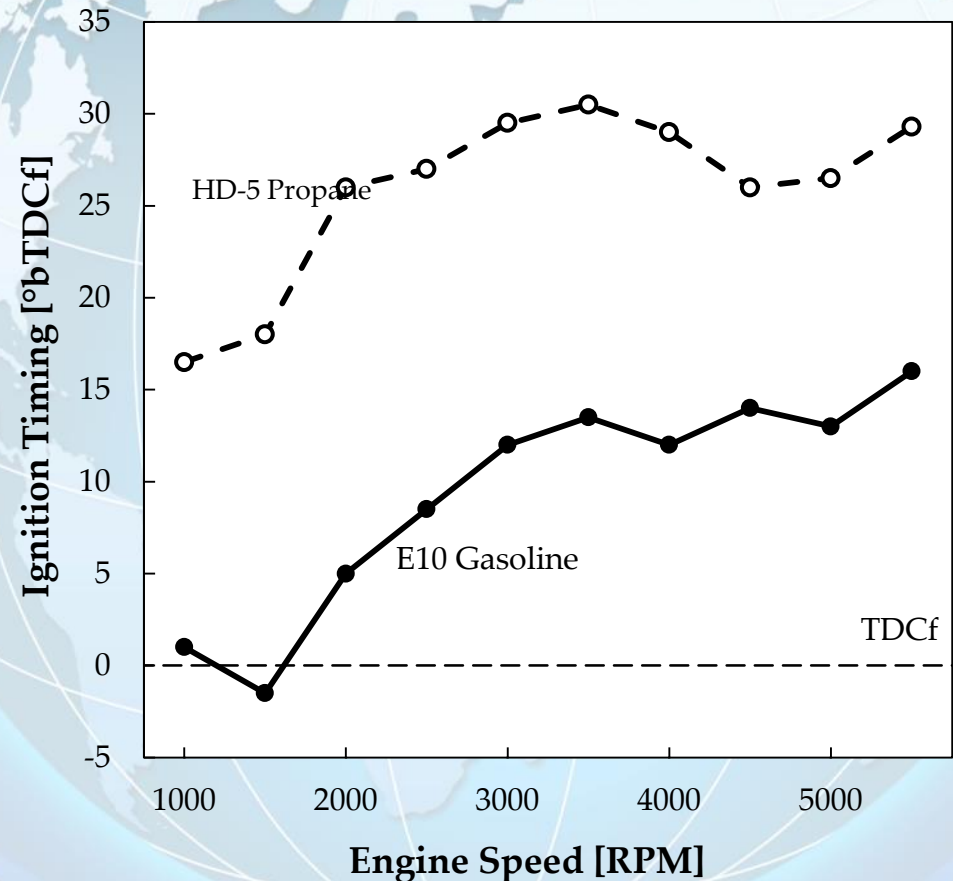
- PERC-funded study to demonstrate LPG injection using stock GDI injection system
- Stock Ford Taurus 3.5 L V6 EcoBoost with intake cam phasers (no exhaust cam phasers), stock ignition and fueling systems, and stock catalysts
- Testing conducted with HD-5 liquid propane and 87 octane E10 Gasoline



Engine installed in
test cell at SwRI

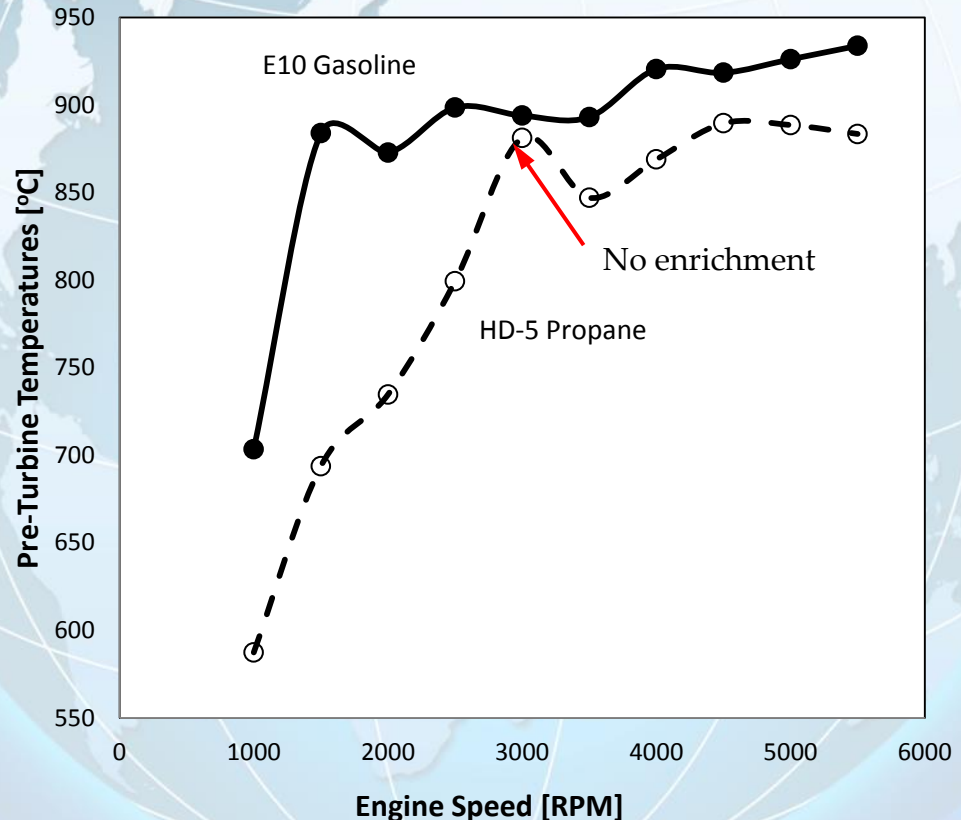
Full Load Ignition Timing

- With HD-5, full load ignition timing could be advanced by 20 degrees
- The knock limit was not reached at any point
- Cylinder pressure and boost were the limiting factors



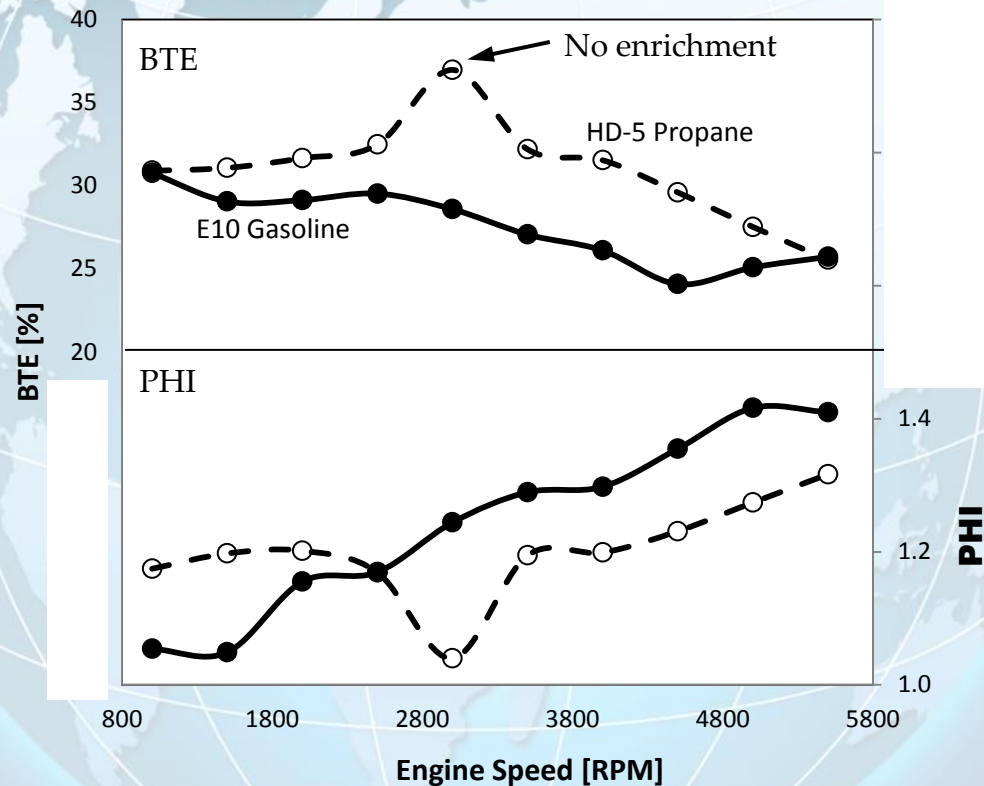
Full Load Exhaust Temperatures

- The 3.5L EcoBoost turbine inlet temperature limit is about 900°C (1650°F)
- Enrichment is required with gasoline to limit exhaust temperature
- Advancing ignition timing reduces exhaust temperature
- HD-5 is within the limit at 3000 RPM without enrichment



Brake Thermal Efficiency

- With HD-5, significantly better thermal efficiency was demonstrated with optimized ignition timing
- At 3000 RPM, the target torque was achieved at an accelerator pedal position that did not trigger enrichment, resulting in additional improvement
- This point demonstrates that further gains are possible if enrichment is reduced





CAFE Incentives

Dual Fuel Incentive Phase-Out

- Dual fuel CAFE benefit currently provided by E85 flex fuel vehicles phases-out in 2020

<u>Model Year</u>	<u>Maximum CAFE increase</u>
Through 2014	1.2 mpg
2015	1.0 mpg
2016	0.8 mpg
2017	0.6 mpg
2018	0.4 mpg
2019	0.2 mpg
2020 and later	0.0 mpg

Ref: 49 USC 32906, 40 CFR 600.510-12(h)

Statutory CAFE Credits for Gaseous Fuels [49 USC 32904(c)]

49 USC 32904(c):

(c) GASEOUS FUEL DEDICATED AUTOMOBILES.—For any model of gaseous fuel dedicated automobile manufactured by a manufacturer after model year 1992, the Administrator shall measure the fuel economy for that model based on the fuel content of the gaseous fuel used to operate the automobile. One hundred cubic feet of natural gas is deemed to contain .823 gallon equivalent of natural gas. The Secretary of Transportation shall determine the appropriate gallon equivalent of other gaseous fuels. A gallon equivalent of gaseous fuel is deemed to have a fuel content of .15 gallon of fuel.

Example: A dedicated propane-fueled pickup getting 18 MPGe would count as 120 MPGe for CAFE

OEM Opportunity

- **Options to take advantage of dedicated CAFE credit in 2020 and beyond:**
 - **Hydrogen fuel cells: no infrastructure**
 - **Battery electric: not viable for pickups**
 - **CNG: range, cost**
 - **LNG: cost**
 - **LPG: best option**

Light-Duty Summary

- **GDI market share is increasing rapidly**
- **GDI enables in-cylinder injection of LPG using stock gasoline injectors (lower cost than existing systems)**
- **LPG enables increased efficiency of turbocharged GDI engines, further reducing CO₂ and fuel cost**
- **LPG produces virtually no particulate emissions in GDI engines, unlike gasoline**
- **GDI engines are available in all popular GM & Ford light-duty fleet applications**
- **OEMs will probably consider offering dedicated LPG vehicles for CAFE credits starting in 2020**



Heavy Duty

Gasoline Derived Spark Ignition

- **Naturally aspirated**
- **Liquid port injection**
- **Examples**
 - **Roush 6.8L V10**
 - **Powertrain Integration Plthon 8.0L V8**
 - **Power Solutions International 8.8L V8**
- **Compete with Cummins 6.7L diesel**
- **Lower efficiency means propane price per gallon must be ~55% of diesel**

Dual Fuel

- **Addition of propane to intake of diesel engines**
- **Typical propane substitution rate 20% of total energy**
- **Minimal impact on BTE**
- **Cost savings possible for Class 8**
- **Unlikely to recover system cost in medium-duty applications**
- **High efficiency dedicated SI engine may be more advantageous**

Cummins ETHOS

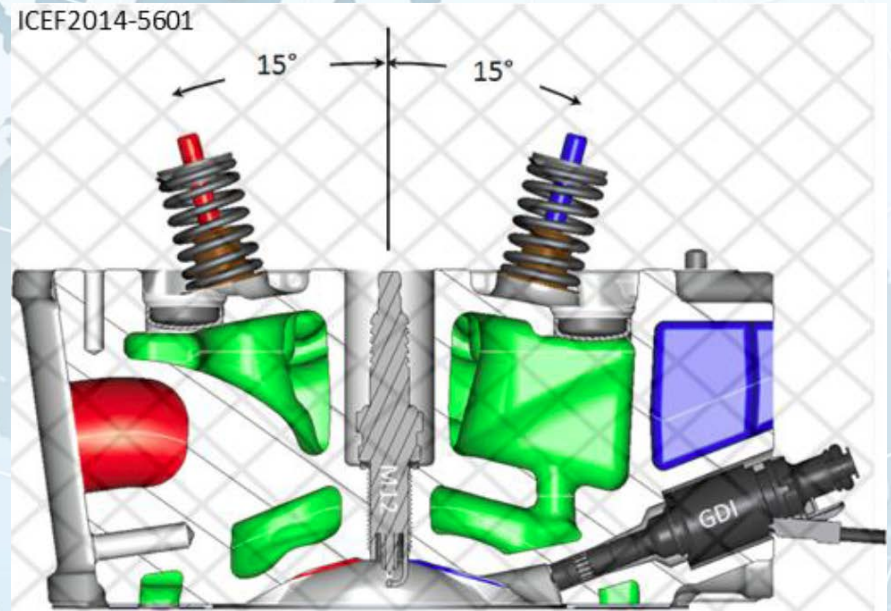


Cummins photo

- Spark ignition 2.8L I-4
- 250 hp @ 3400 RPM
- 440 lb-ft @ 1400 RPM
- 170 bar max cyl pressure
- 12:1 compression ratio
- Single stage turbo
- No EGR
- 490 lbs dry weight
- Al block w/ iron liners
- Aluminum head
- Aluminum pistons
- Start-stop system

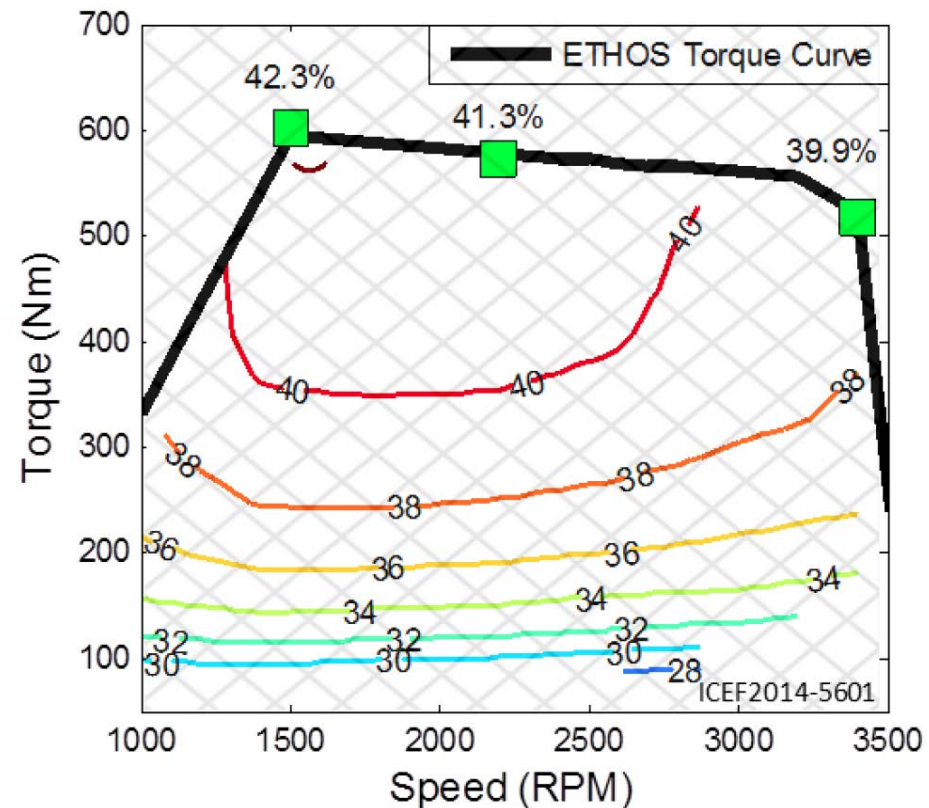
Cummins ETHOS

- SI-optimized pent roof head
- DOHC 4-valve
- Direct injection (200 bar max pressure)
- Coil on plug ignition
- M12 iridium plug
- Independent intake & exhaust valve timing
- Dual cam profiles



Cummins ETHOS

- 27 bar max BMEP
- > 30% BTE above 5 bar BMEP
- > 40% BTE above 15 bar BMEP
- 3.7% fuel cost savings over HTUF cycle on E85 compared to 6.7L diesel
 - E85 \$3.19 / gal
 - Diesel \$4.40 / gal



ASME Paper ICF2014-5601

Heavy Duty Summary

- **Current SI engines require a large price differential between propane and diesel to be viable**
- **Dual fuel is only cost effective for applications with very high fuel consumption due to low substitution rates**
- **No dedicated propane engines exist for Class 8**

Heavy Duty Summary

- **Propane enables high efficiency SI heavy duty engines**
 - **Cost competitive with diesel engines at lower fuel price differential**

Needs

- **For light-duty DI**
 - Efficiency demonstration
 - Engine durability testing
 - Pump and injector durability
 - Injector and combustion chamber deposits
 - Valve recession
 - Lubricant performance
 - Emissions durability
- **For heavy-duty high-efficiency engine**
 - Willing engine manufacturer
 - Development funding



SOUTHWEST RESEARCH INSTITUTE



Backup Slides



2015 DI Vehicles

GM Direct Injected Engines

RPO	Config	Power	Torque	Applications
LHU LTG	2.0L I-4 turbo	250-272 hp	260-295 lb-ft	ATS, CTS, Malibu, Regal, Verano
LEA LUK	2.4L I-4	180-182 hp	171-172 lb-ft	Regal, LaCrosse, Verano, Equinox*, Terrain*
LCV LKW	2.5L I-4	196-202 hp	186-191 lb-ft	ATS, Impala, Malibu, Colorado, Canyon
LLT LFX	3.6L V-6	281-323 hp	262-278 lb-ft	ATS, CTS, XTS, Camaro, Caprice PPV*, Impala*, LaCrosse*, Acadia, Enclave, Traverse, Equinox, Terrain, SRX, Colorado, Canyon
LF3	3.6L V-6 turbo	410-420 hp	369-430 lb-ft	CTS, XTS
LV3	4.3L V-6	285 hp	305 lb-ft	Silverado*, Sierra*
L83	5.3L V-8	355 hp	383 lb-ft	Silverado*, Sierra*, Suburban, Tahoe, Yukon
L86	6.2L V-8	420 hp	450 lb-ft	Silverado, Sierra, Escalade, Yukon
LT1	6.2L V-8	455-460 hp	460-465 lb-ft	Corvette
LT4	6.2L V-8	650 hp	650 lb-ft	Corvette Z06

* Flex Fuel

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Ford Direct Injected Engines

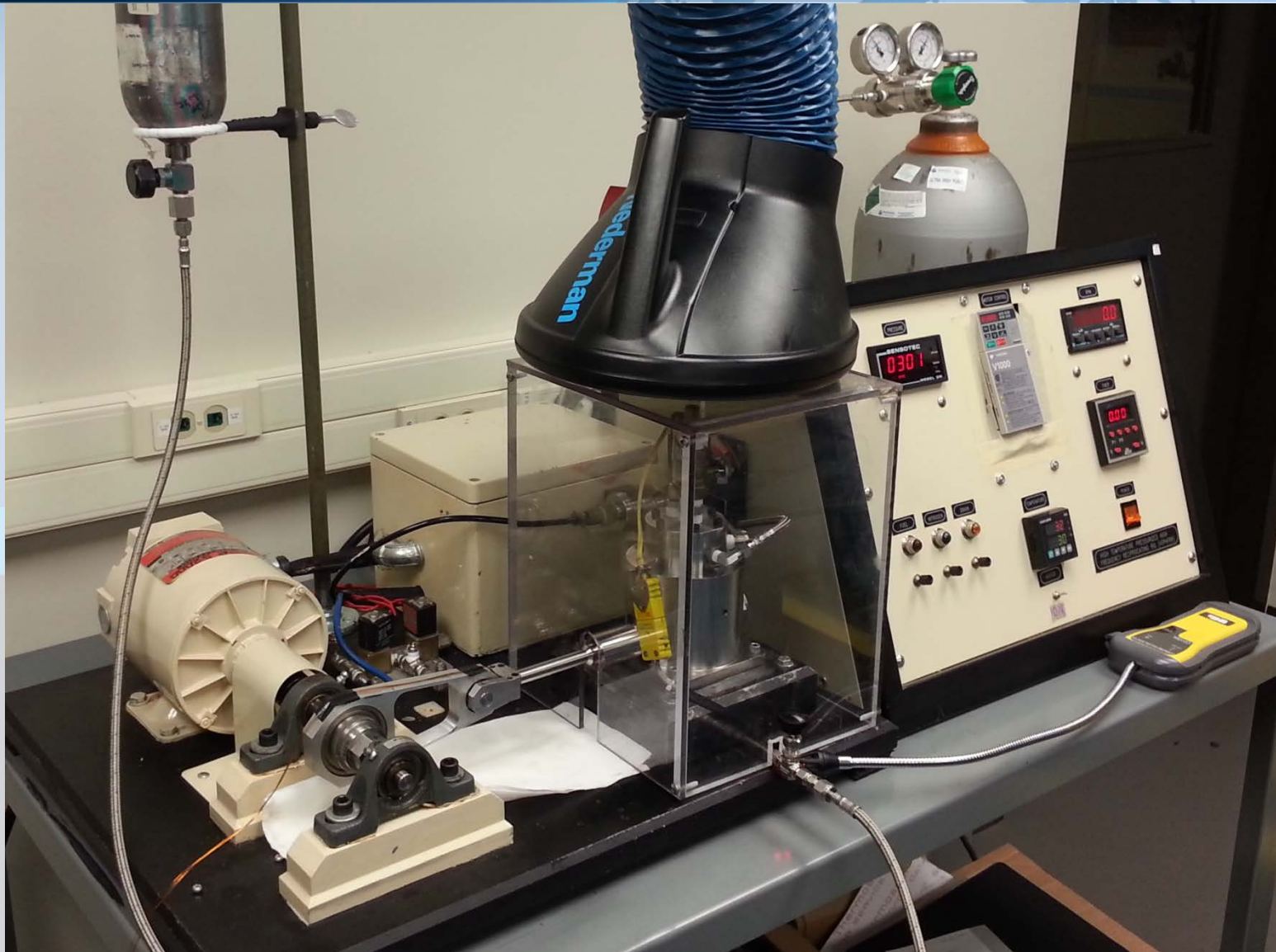
Config	Power	Torque	Applications
1.0L I-3 turbo	123 hp	125 lb-ft	Fiesta, Focus
1.5L I-4 turbo	178 hp	177 lb-ft	Fusion
1.6L I-4 turbo	178-197 hp	184-202 lb-ft	Fiesta ST, Escape, Transit Connect
2.0L I-4	160 hp	146 lb-ft	Focus*
2.0L I-4 turbo	240-252 hp	270 lb-ft	Focus ST, Fusion, Taurus Escape, Edge, Explorer, MKC, MKZ
2.3L I-4 turbo	285-310 hp	305-320 lb-ft	MKC, Mustang
2.7L V-6 turbo	325 hp	375 lb-ft	F-150
3.5L V-6 turbo	310-380 hp	350-460 lb-ft	Taurus SHO, Flex, Explorer, Expedition, F-150, Police Sedan & Utility, Transit, MKS, MKT, Navigator

* Flex Fuel

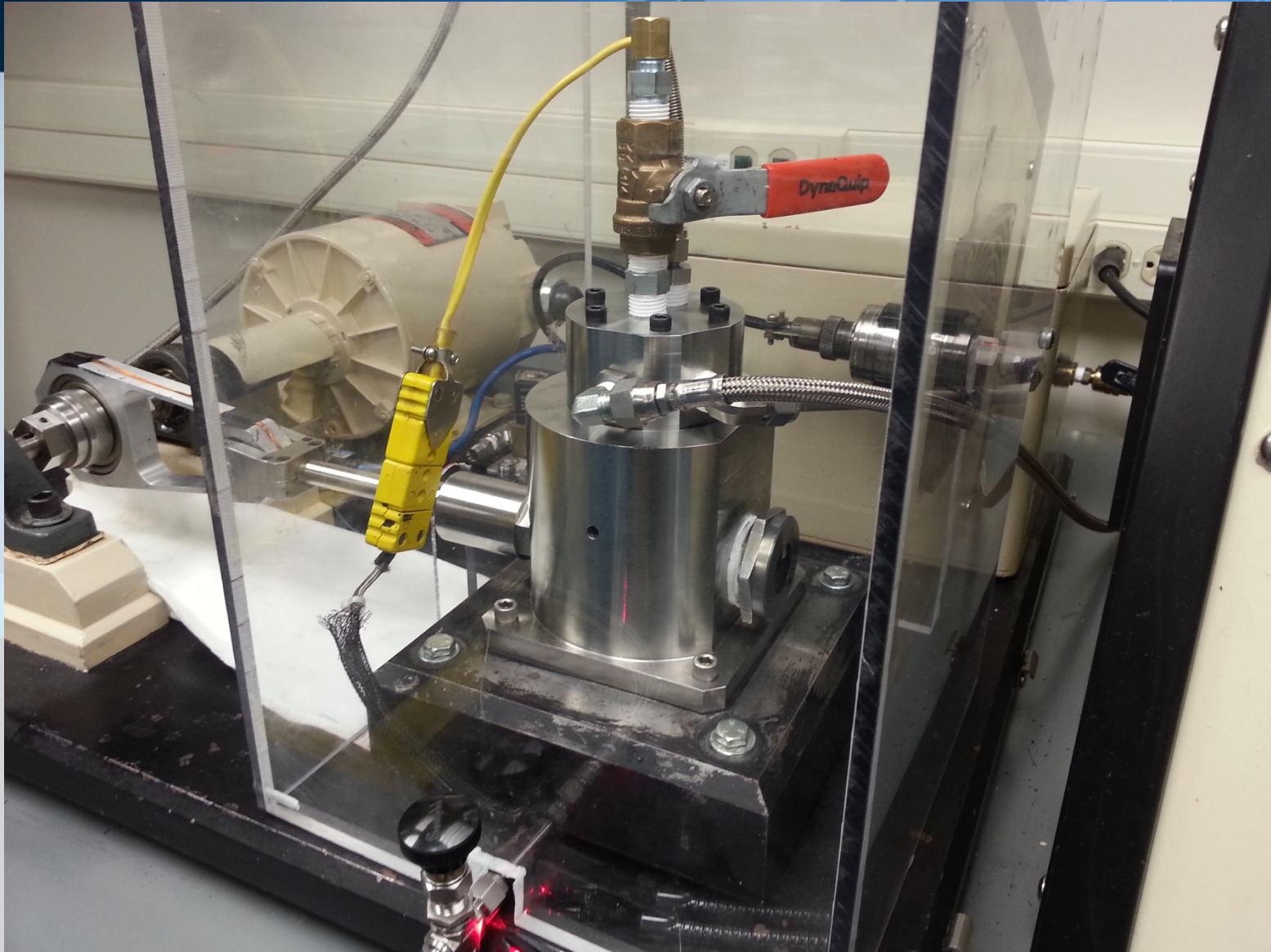


Propane Lubricity Testing

High-Temperature and Pressure High Frequency Reciprocating Rig



HTP HFRR Test Chamber



Test Plan

Wear Severity @ 225 Meters

Run Number	Temperature (°C)	Pressure (psi)	Frequency (Hz)	Stroke (mm)	Time (min:sec)
1	30	300	50	1	75:00
2	40	300	40	1	93:45
3	55	300	20	1.5	125:00

Fuel 1 – E10, no additives, Haltermann

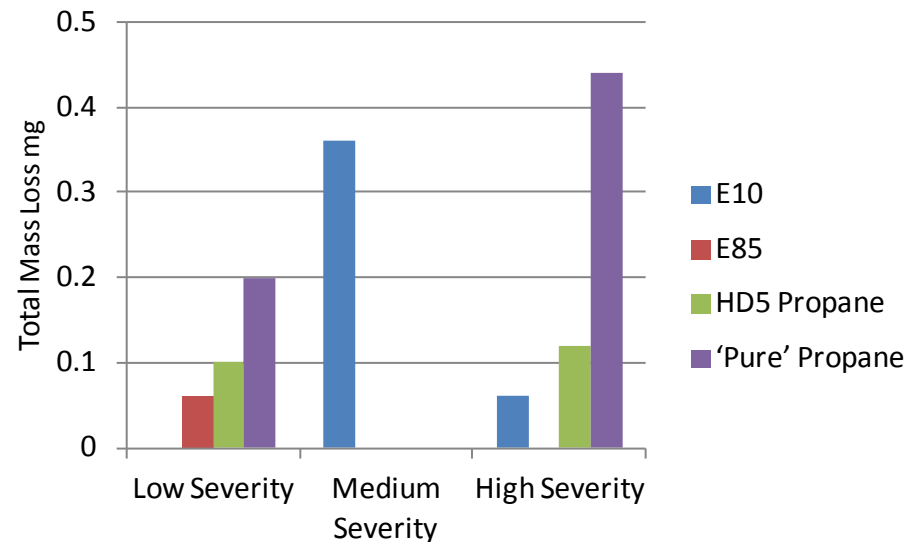
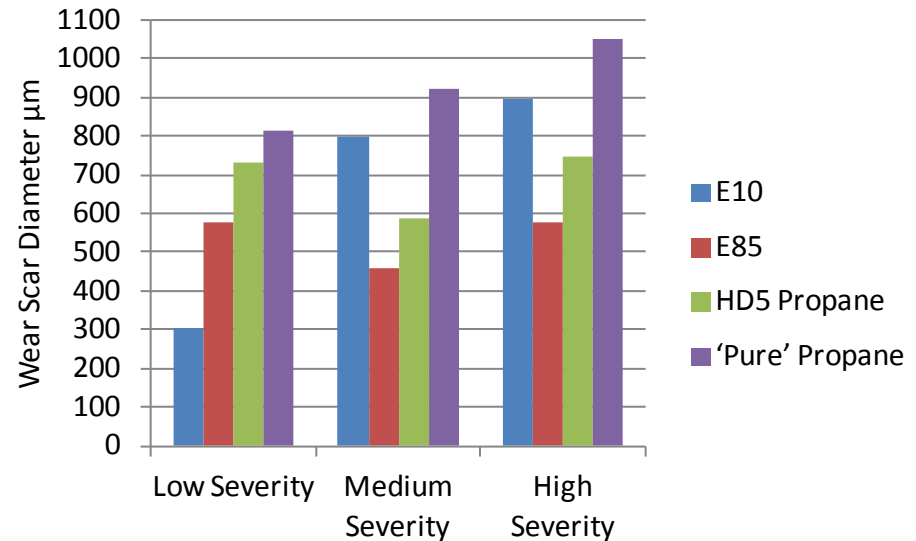
Fuel 2 – E85, no additives, Haltermann

Fuel 3 – HD5 Propane, Airgas Texas

Fuel 4 – ‘Pure’ Propane, Airgas California

Results

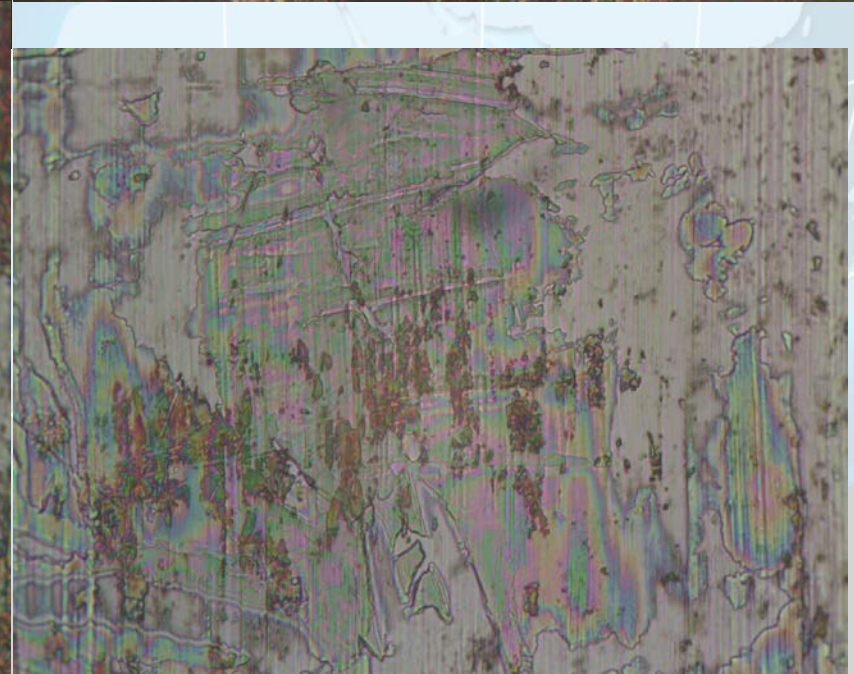
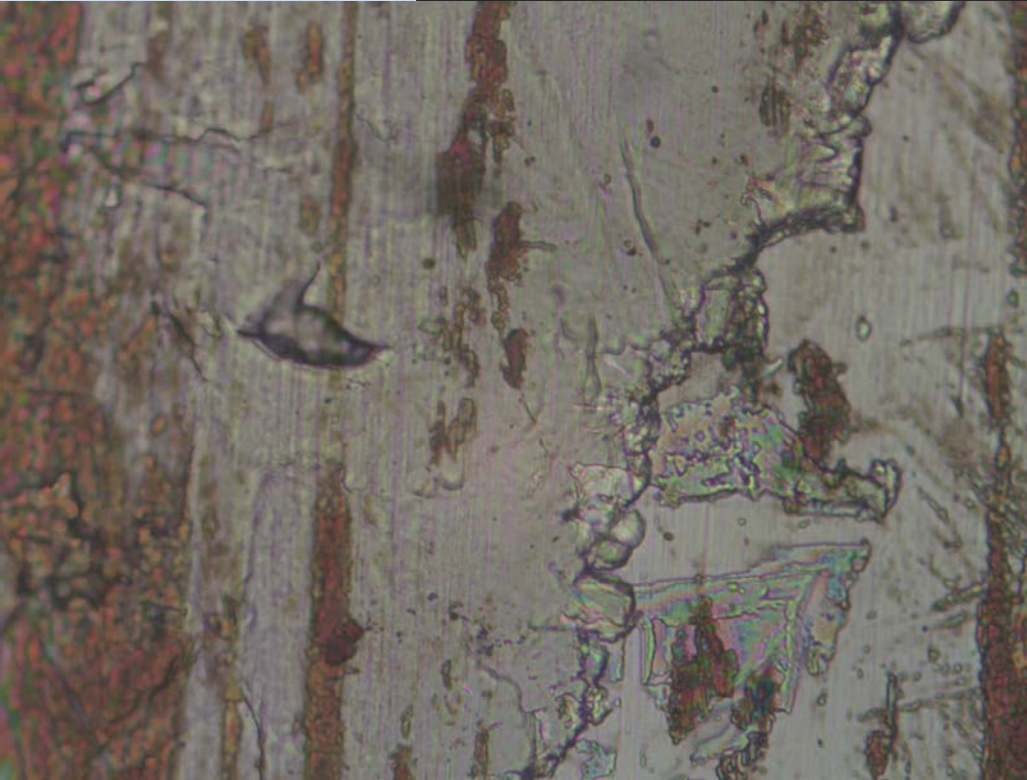
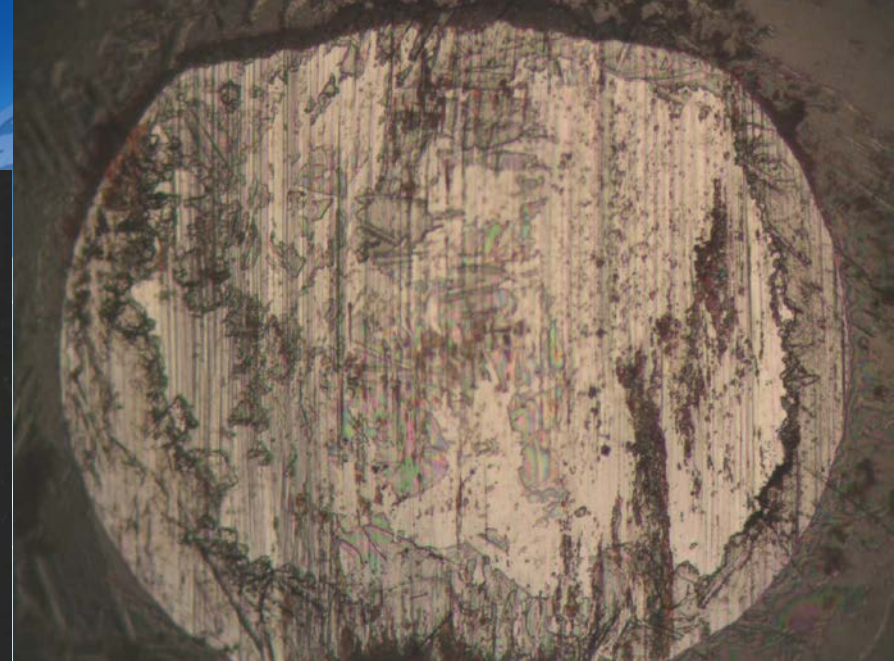
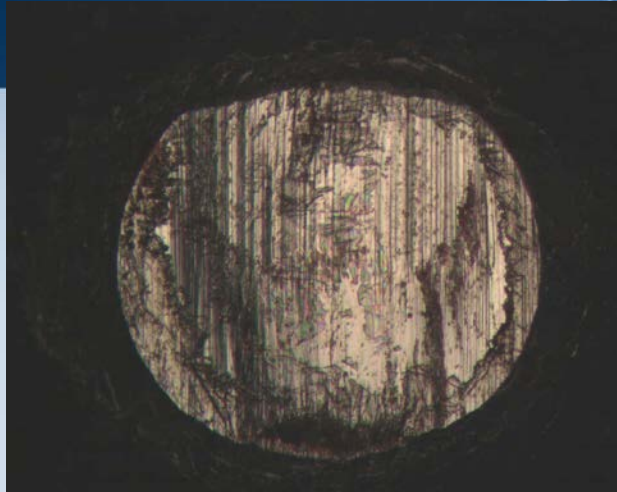
- Wear ranking seems intuitive at low severity condition
- E85 and HD5 follow similar trend – low and high severity are equal with medium severity exhibiting lower values
- E10 and 'Pure' show increasing wear with increasing severity
- E10 high wear on ball at medium severity
- 'Pure' Propane high wear on disk at high severity



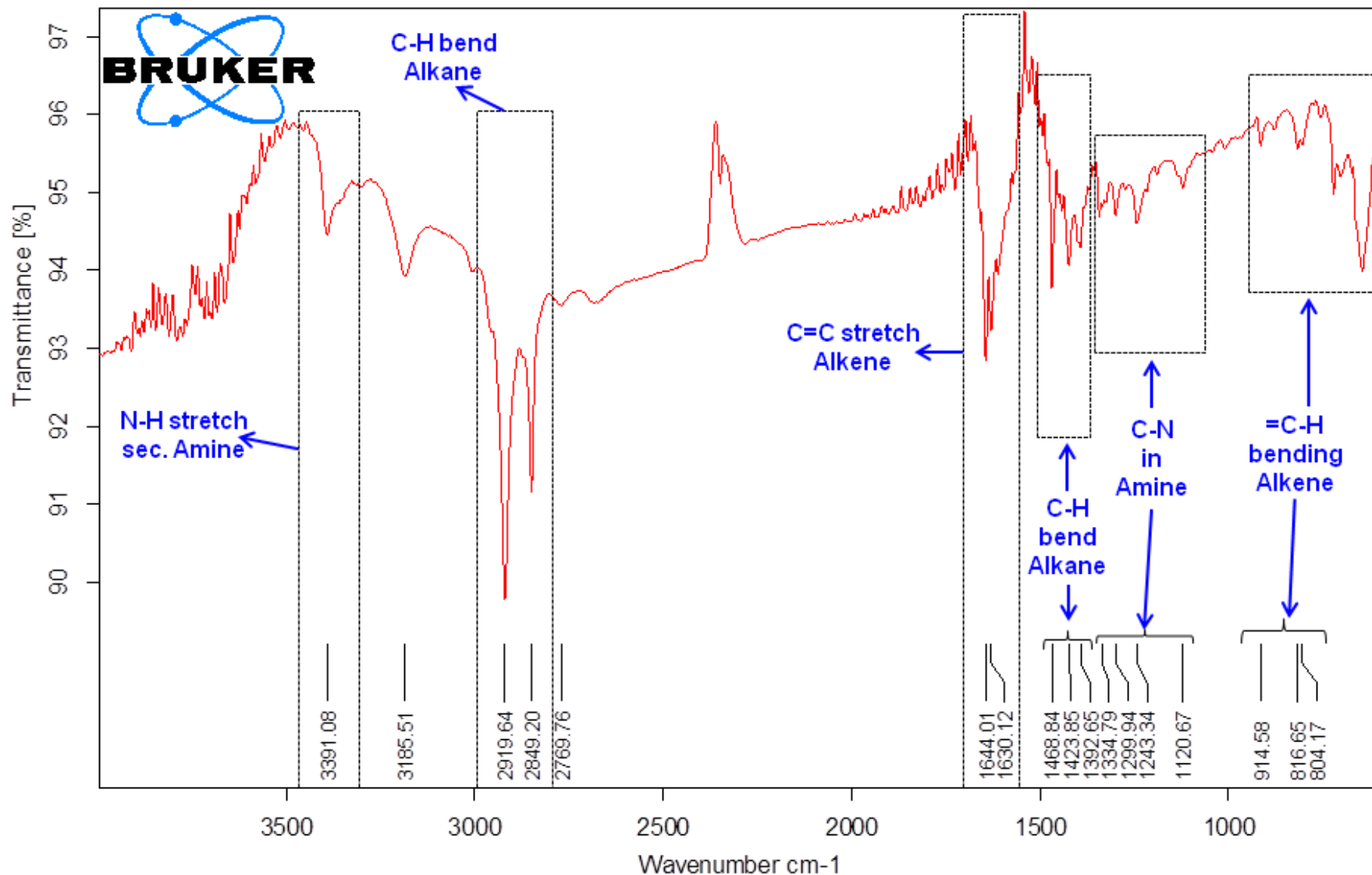
Observations

**'Pure' Propane
Deposits**

Medium Severity



FTIR – Looks like Plastic



Contaminants

- Residue by DaVinci
 - HD5
 - Total – 15 ppm
 - (C16+) – 12.3 ppm
 - (C20+) – 11.4ppm
 - ‘Pure’
 - Total – 9.9 ppm
 - (C16+) – 9.1 ppm
 - (C20+) – 7.3 ppm

Relevance of Results

- Compare our results to a study done in 2011:

- 25 C, 50 Hz, 75 minutes [Our Low Wear Condition]
- 36 Unadditized Gasoline Samples
 - WSD from 711 to 1064
- 136 Additized Gasoline Samples
 - WSD from 279 to 846
- Concluded that HFRR WSD is only dependent on Bulk Constituents

Lubricity assessment of gasoline fuels
P. Arkoudeas , D. Karonis, F. Zannikos, E. Lois
National Technical University of Athens, School of Chemical
Engineering, Iroon Polytechniou 9, Athens 157 80, Greece

- Jet Fuel Related Work at SwRI

- Diesel HFRR Spec is 520 @ 60 C
- Jet Fuel (unadditized) may be as high as 850 and is used in ARMY ground vehicles
 - This will completely fail injection pumps
- HFRR WSD is typically insensitive to minor treat rates of CILI (5-25 ppm)
 - Injection pumps will last their intended lifetime if Jet Fuel is treated at this level
- In order to 'see results' on HFRR, Diesel additive rates may be 4-5x higher than their effective dose

Summary

- HD5 HFRR test results fall within the gasoline and ethanol range
- HD5 largely insensitive to wear severity
- HD5 and 'Pure' Propane exhibited similar levels of contaminants
- Wear performance benefit of HD5 likely due to propylene fraction



Statutory Gasoline Gallon Equivalents

Defined Gasoline Gallon Equivalents

49 CFR 538.8

TABLE I—GALLON EQUIVALENT MEASUREMENTS
FOR GASEOUS FUELS PER 100 STANDARD
CUBIC FEET

Fuel	Gallon equivalent measurement
Compressed Natural Gas	0.823
Liquefied Natural Gas	0.823
Liquefied Petroleum Gas (Grade HD-5)*	0.726
Hydrogen	0.259
Hythane (Hy5)	0.741

* Per gallon unit of measure.